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On Galois module structure of the cohomology
groups of an algebraic variety

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§ 1. Main results

Let k be a field and $f : X \longrightarrow Y$ a finite Galois covering between projective varieties X and Y over k . Put $G = \text{Gal}(X/Y)$. A coherent sheaf \mathcal{F} on X is called a coherent G -sheaf when the group G acts on \mathcal{F} in a way compatible with its action on X . For a coherent G -sheaf \mathcal{F} on X , the group G naturally acts on the cohomology groups $H^i(X, \mathcal{F})$ ($i \geq 0$). We are concerned with the $k[G]$ -module structure of $H^i(X, \mathcal{F})$ ($i \geq 0$).

Our general result is the following two theorems.

Theorem 1. Assume that $f : X \longrightarrow Y$ is tamely ramified, i.e. for any geometric point $\bar{\eta}$ of X , the order of its stabilizer group $G_{\bar{\eta}}$ in G is prime to $\text{char } k$. Then for a coherent G -sheaf \mathcal{F} on X , we have a finite complex

$$(M) : 0 \longrightarrow M^0 \longrightarrow M^1 \longrightarrow \dots \longrightarrow M^m \longrightarrow 0$$

of $k[G]$ -modules with the following properties :

- (1) Each M^i is a finitely generated projective $k[G]$ -module.
 (2) The i -th cohomology group of the complex (M) is isomorphic to $H^i(X, \mathcal{F})$ as a $k[G]$ -module ($i = 0, 1, 2, \dots$) .

Theorem 2. In the situation of Theorem 1 , assume further that f is unramified, i.e. $G_{\bar{\eta}} = \{1\}$ for any geometric point $\bar{\eta}$ of X . Then, concerning the complex (M) in Theorem 1 , we can replace the condition (1) by the following stronger condition (1)' :

- (1)' Each M^i is a finitely generated free $k[G]$ -module.

As a direct consequence of Theorems 1 and 2 , we give Corollary below, which seems most useful in application.

Corollary. For a coherent G -sheaf \mathcal{F} on X , assume that $H^i(X, \mathcal{F}) = 0$ for all i except one value, say i_0 , of i . Then, when f is tamely ramified, the remaining cohomology group $H^{i_0}(X, \mathcal{F})$ is a projective $k[G]$ -module. Further, if f is unramified, $H^{i_0}(X, \mathcal{F})$ is a free $k[G]$ -module.

Remarks. (1) When the algebra $k[G]$ is semi-simple (i.e. when $\text{char } k$ does not divide the order of G) , all $k[G]$ -modules are projective and the property (1) of the complex (M) in Theorem 1 is trivial. However, when $k[G]$ is not semi-simple, it is a good information about a $k[G]$ -module that it is $k[G]$ -projective.

(2) The complex (M) in Theorems 1 or 2 is never unique. We can change the modules M^i ($i \geq 0$) in many ways keeping the conditions (1) (or (1)') and (2). For example, in Theorem 1, we can take a complex (M) for which each M^i is a free $k[G]$ -module for $i \geq 1$ (i.e. except M^0).

(3) Theorem 2 is proved in [3]. Although Theorem 1 is not written explicitly in [3], it is essentially proved in the course of the proof of Theorem 2.

The motivation of this work was to generalize Chevalley-Weil's theorem to arbitrary characteristic. Chevalley-Weil [1] treats a finite Galois covering $f : X \rightarrow Y$ of connected complete non-singular algebraic curves X and Y over the complex number field \mathbb{C} (i.e. X and Y are compact Riemann surfaces), and determines the $\mathbb{C}[G]$ -module structure ($G = \text{Gal}(X/Y)$) of $H^0(X, \mathcal{K})$, where \mathcal{K} is the canonical sheaf of X . ($H^0(X, \mathcal{K})$ is the space of holomorphic differentials on X .) Their theorem is obtained by calculating, using the Riemann-Roch theorem, the character of the $\mathbb{C}[G]$ -module $H^0(X, \mathcal{K})$. If one tries to generalize Chevalley-Weil's theorem to arbitrary characteristic, i.e. to arbitrary base field k , difficulties arise as to the case where $p = \text{char } k$ divides $|G|$, the order of G . Even in this case we can calculate the Brauer character of the $k[G]$ -module $H^0(X, \mathcal{K})$ by use of the Riemann-Roch theorem, but, when p divides $|G|$, the knowledge of the Brauer character does not suffice to determine the $k[G]$ -module

structure of $H^0(X, \mathcal{K})$ since the algebra $k[G]$ is no longer semi-simple. The author found that this difficulty can be overcome by making good use of (*) mentioned below (for (*), see [4] § 16 or [2] chap. 2). (Although $H^0(X, \mathcal{K})$ itself is not necessarily $k[G]$ -projective, we can determine its $k[G]$ -module structure by embedding it into some other $k[G]$ -module whose structure is determined by virtue of (*).)

(*) ... If two finitely generated projective $k[G]$ -modules have the same Brauer character, then they are isomorphic as $k[G]$ -modules.

The generalization of Chevalley-Weil's theorem to the case of arbitrary base field is given in the next section. It was pointed out by Professor J-P. Serre that the method adopted in the case of curves is also effective in higher dimensional cases, and Theorems 1 and 2 were obtained following his suggestion.

§ 2. The case of curves

In this section we apply the general results of § 1 to the special case where X and Y are of dimension one and the G -sheaf \mathcal{F} is locally free.

Let k be an algebraically closed field of characteristic p ($p \geq 0$), and let $f : X \rightarrow Y$ be a finite Galois covering of connected complete non-singular curves over k . Put $G = \text{Gal}(X/Y)$. We assume that f is tamely ramified. To state

our result, some notations are necessary. For each point P of X , put $G_P = \{ \sigma \in G \mid \sigma \cdot P = P \}$ (the stabilizer of P) and $e_P = |G_P|$. We have $e_P = 1$ except for a finite number of P . Since f is tamely ramified, G_P is a cyclic group of order $(= e_P)$ prime to $p = \text{char } k$.

Define $\Theta_P \in \text{Hom}(G_P, k^\times)$ by

$$\Theta_P(\sigma) = \frac{\sigma \cdot \pi}{\pi} \pmod{(\pi)} \quad \text{for } \sigma \in G_P,$$

where $\pi = \pi_P$ denotes a local uniformizing parameter at P .

Then Θ_P is a generator of the group $\text{Hom}(G_P, k^\times)$. For $d \in \mathbb{Z}$, we also use the symbol Θ_P^d to denote the one-dimensional $k[G]$ -module corresponding to $\Theta_P^d \in \text{Hom}(G_P, k^\times)$.

Suppose that a locally free G -sheaf \mathcal{E} of rank r on X is given. Then for $P \in X$ the group G_P acts on the stalk \mathcal{E}_P of \mathcal{E} at P . The $k[G_P]$ -module $\mathcal{E}_P \otimes_{\mathcal{O}_P} k$ (\mathcal{O}_P is the stalk at P of the structure sheaf \mathcal{O} of X) decomposes into a

direct sum of one-dimensional $k[G_P]$ -modules because $p \nmid e_P$

and G_P is cyclic. Define integers $l_{P,i}$ ($0 \leq l_{P,i} \leq e_P - 1$) for $P \in X$ and $i = 1, \dots, r$ so that $\mathcal{E}_P \otimes_{\mathcal{O}_P} k$ is isomorphic

to $\bigoplus_{i=1}^r \Theta_P^{-l_{P,i}}$ as a $k[G]$ -module. (We have $l_{P,i} = 0$ for all P and i if \mathcal{E} is of the form $f^*(\mathcal{G})$ for a locally free sheaf \mathcal{G} on Y .)

With the above notation, the result is as follows. (For a $k[G]$ -module L and $n \in \mathbb{N}$, nL means the n -times direct sum of L .)

Theorem 3. (i) There exists a $k[G]$ -module N such that

$$|G| \cdot N \cong \bigoplus_{P \in X} \text{Ind}_{G_P}^G \left(\bigoplus_{d=0}^{e_P-1} d \cdot \theta_P^d \right)$$

as $k[G]$ -modules.

(ii) Let \mathcal{E} be a locally free G -sheaf of rank r on X and let $l_{P,i}$ be as defined above. Then we have two finitely generated $k[G]$ -modules M^0 and M^1 with the following properties :

(a) We have an exact sequence

$$0 \longrightarrow H^0(X, \mathcal{E}) \longrightarrow M^0 \longrightarrow M^1 \longrightarrow H^1(X, \mathcal{E}) \longrightarrow 0$$

of $k[G]$ -modules.

(b) The modules M^0 and M^1 are $k[G]$ -projective and $M^0 \oplus r \cdot N$ (N is the module defined in (i)) is stably isomor-

phic to $M^1 \oplus \bigoplus_{Q \in Y} \bigoplus_{i=1}^r \bigoplus_{d=1}^{l_{P,i}} \text{Ind}_{G_Q}^G (\theta_Q^{-d})$ as a $k[G]$ -module,

where for $Q \in Y$, \tilde{Q} denotes an (arbitrarily fixed) point of X such that $f(\tilde{Q}) = Q$ holds, and the sum denoted by

$\bigoplus_{i=1}^{l_{P,i}}$ means empty sum when $l_{P,i} = 0$.

Remarks. (1) The $k[G]$ -module N in Theorem 3 (i) is determined by the covering $f : X \longrightarrow Y$ (independent of sheaves), and reflects the state of ramification of f . The module N can be defined only "globally". This means that

each $k[G]$ -module $\text{Ind}_{G_P}^G \left(\bigoplus_{d=0}^{e_P-1} d \cdot \Theta_P^d \right)$ for $P \in X$ is not divisible by $|G|$ in general while their sum over all $P \in X$ is always divisible by $|G|$.

(2) If the $k[G]$ -module structure of either of the two modules $H^0(X, \mathcal{E})$ and $H^1(X, \mathcal{E})$ is known, we can determine by Theorem 3 the $k[G]$ -module structure of the other (cf. Schanuel's lemma, [2] (2.24)). In this sense, Theorem 3 gives a "relation" between $k[G]$ -modules $H^0(X, \mathcal{E})$ and $H^1(X, \mathcal{E})$.

As for the canonical sheaf \mathcal{K} of X , we know that $H^1(X, \mathcal{K}) \cong k$ as $k[G]$ -modules, where k denotes the trivial $k[G]$ -modules. Hence, by Theorem 3, the $k[G]$ -module structure of $H^0(X, \mathcal{K})$ can be determined. (We have $l_{P,i} = e_P - 1$ in this case.) For the sake of simplicity, we restrict ourselves to the case where f is unramified, i.e. $e_P = 1$ for all $P \in X$. Denote by I_G the augmentation ideal of $k[G]$; $I_G = \left\{ \sum_{\sigma \in G} a_\sigma \cdot \sigma \in k[G] \mid \sum_{\sigma \in G} a_\sigma = 0 \right\}$. Then we have

Theorem 4. Assume that $f : X \rightarrow Y$ is unramified and let \mathcal{K} be the canonical sheaf of X . Then we have an exact sequence of $k[G]$ -modules

$$0 \rightarrow H^0(X, \mathcal{K}) \rightarrow k[G]^g \rightarrow I_G \rightarrow 0,$$

where g is the genus of Y . This exact sequence uniquely determines the $k[G]$ -module structure of $H^0(X, \mathcal{K})$.

When $\text{char } k = 0$, the exact sequence in Theorem 4 splits for every group G , and consequently we have $H^0(X, \mathcal{K}) \cong k \oplus k[G]^{g-1}$ as $k[G]$ -modules. (This isomorphism is proved in Chevalley-Weil [1].) However, when $\text{char } k > 0$, that exact sequence does not necessarily split. Hence we find that, when $\text{char } k > 0$, the $k[G]$ -module $H^0(X, \mathcal{K})$ is not isomorphic to $k \oplus k[G]^{g-1}$ in general, in contrast to the case $\text{char } k = 0$.

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